Advanced Packaging for 5G in RF and Analog Mixed Signal

IEEE HIR 5G mm-waves TWG Chair
Tim Lee (The Boeing Company)

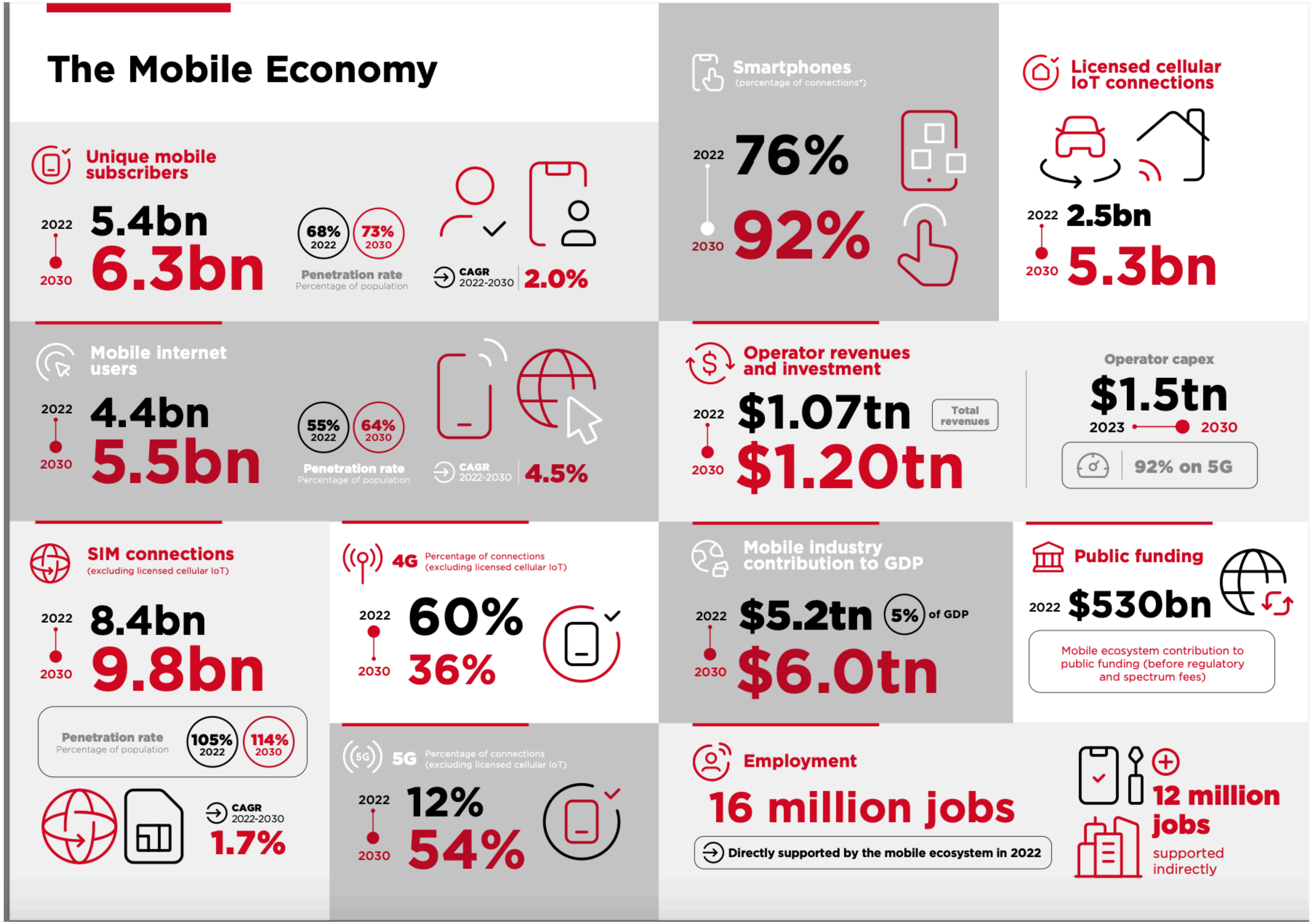
February 2024

Boeing Technical Fellow, BR&T
2024 IEEE-USA President-Elect
IEEE FNTC Vice-Chair
IEEE HIR TWG Co-Chair
Past President, IEEE MTT-S

Timothy Lee, currently a Boeing Technical Fellow, is responsible for the development of RF and digital electronics for advanced communications networks and sensor systems. In the IEEE, Tim is promoting the use of technology to benefit humanity.

Technology Roadmaps to Enable the 5G Ecosystem

- Microwave / millimeter-wave RF-Front Modules needed for emerging 5G User Equipment (UE) and Base-stations (BS)
- Roadmaps for Hardware and Advanced Packaging to guide us to areas of research for millimeter-wave RF Front-Ends for 5G and Beyond
- Time horizons: 3-, 5- and 10-years
- Addressing Semiconductors and Advanced Packaging technical trades
- Devices, materials, processes and substrates needed to support the goal of low-cost high performance 5G New Radio (NR) hardware
- Initial look at beyond 5G for technology needs between 100 GHz to 1 THz (6G)



The Mobile Economy

Unique mobile subscribers
2022 5.4bn
2030 6.3bn
68% 2022 | 73% 2030
Penetration rate
Percentage of population
CAGR 2022-2030 2.0%

Smartphones
(percentage of connections*)
2022 76%
2030 92%

Licensed cellular IoT connections
2022 2.5bn
2030 5.3bn

Mobile internet users
2022 4.4bn
2030 5.5bn
55% 2022 | 64% 2030
Penetration rate
Percentage of population
CAGR 2022-2030 4.5%

Operator revenues and investment
2022 $1.07tn
2030 $1.20tn
Total revenues

Operator capex
$1.5tn
2023 – 2030
92% on 5G

SIM connections
(excluding licensed cellular IoT)
2022 8.4bn
2030 9.8bn
Penetration rate
Percentage of population
105% 2022 | 114% 2030
CAGR 2022-2030 1.7%

4G Percentage of connections (excluding licensed cellular IoT)
2022 60%
2030 36%

5G Percentage of connections (excluding licensed cellular IoT)
2022 12%
2030 54%

Mobile industry contribution to GDP
2022 $5.2tn 5% of GDP
2030 $6.0tn

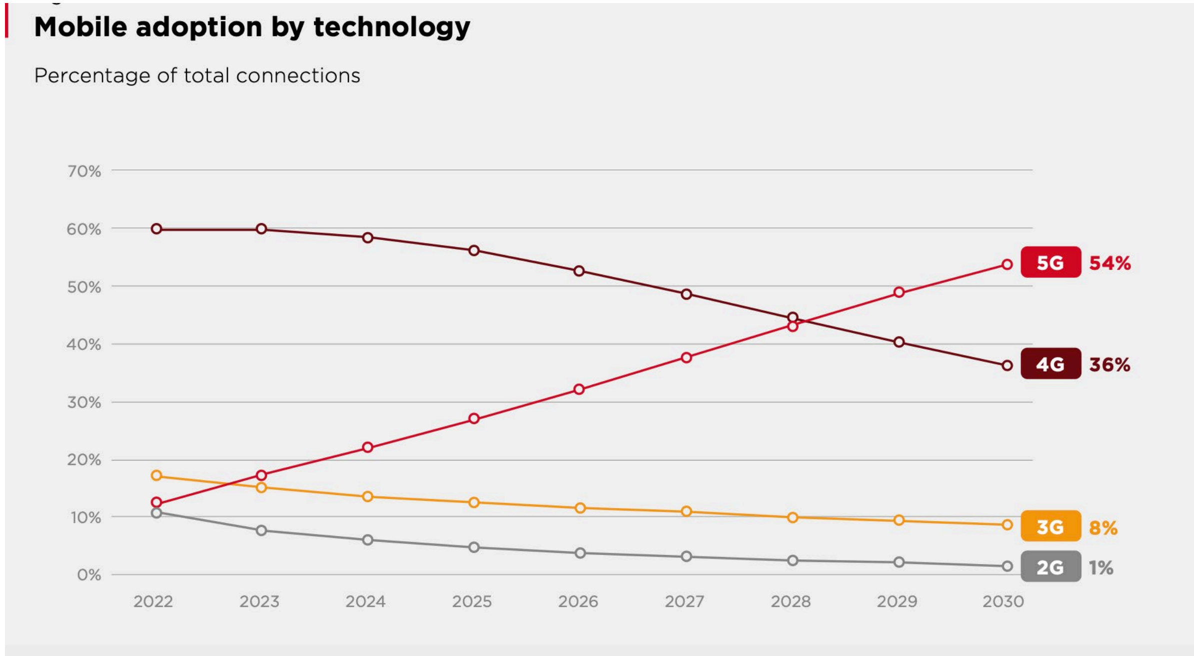
Public funding
2022 $530bn
Mobile ecosystem contribution to public funding (before regulatory and spectrum fees)

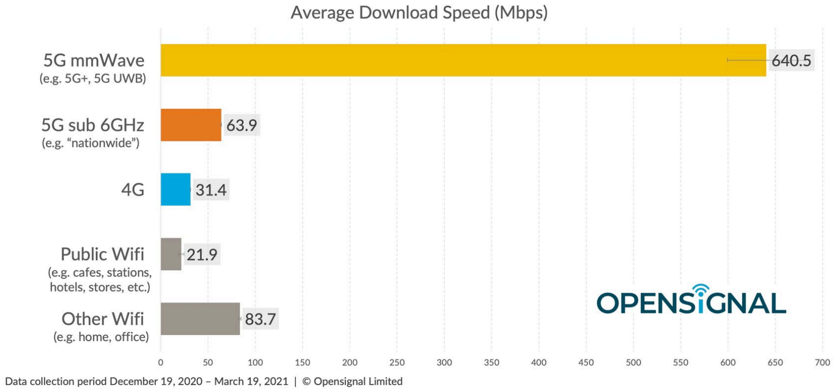
Employment
16 million jobs
Directly supported by the mobile ecosystem in 2022
12 million jobs supported indirectly

https://www.gsma.com/mobileeconomy/

Status of 5G Deployments in 2024 (GSMA Report)

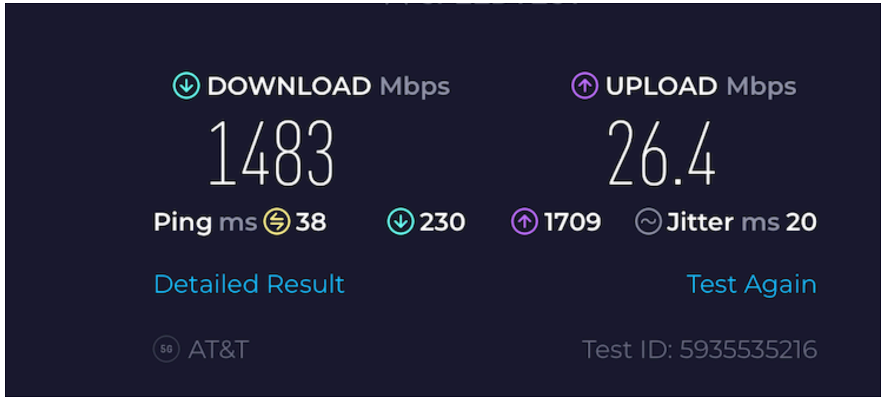
The 5G Era has begun and gaining momentum!





Data collection period December 19, 2020 – March 19, 2021 | © Opensignal Limited

- C-Band: 3.7GHz to 3.98GHz turned on in US



DOWNLOAD Mbps 1483

UPLOAD Mbps 26.4

Ping ms 38 230 1709 Jitter ms 20

AT&T

Test ID: 5935535216

AT&T 5G+ SpeedTest at CES 2024 in Las Vegas Convention Center (**mm-waves**)

https://www.gsma.com/mobileeconomy/

Digital Connectivity: A Transformative Opportunity

- The events of the last three years, with a global health pandemic and the swift international pivot to digital delivery of goods, services, work, and play, have yielded unique insights into just how critical stable, broadband access is and will continue to be. While the global markets still face strong economic headwinds today, digital connectivity has accelerated as people, businesses, and governments pivoted strongly towards online communications, and we continue to see new internet devices and applications, growing broadband penetration into developing markets.
- We won't rest until we live in a world where meaningful connectivity is a lived reality fo everyone, everywhere."

2025 Advocacy Targets for Bridging the Digital Divide

TARGET 1
MAKE BROADBAND POLICY UNIVERSAL

TARGET 2
MAKE BROADBAND AFFORDABLE

TARGET 3
GET EVERYONE ONLINE

TARGET 4
PROMOTE DIGITAL SKILLS DEVELOPMENT

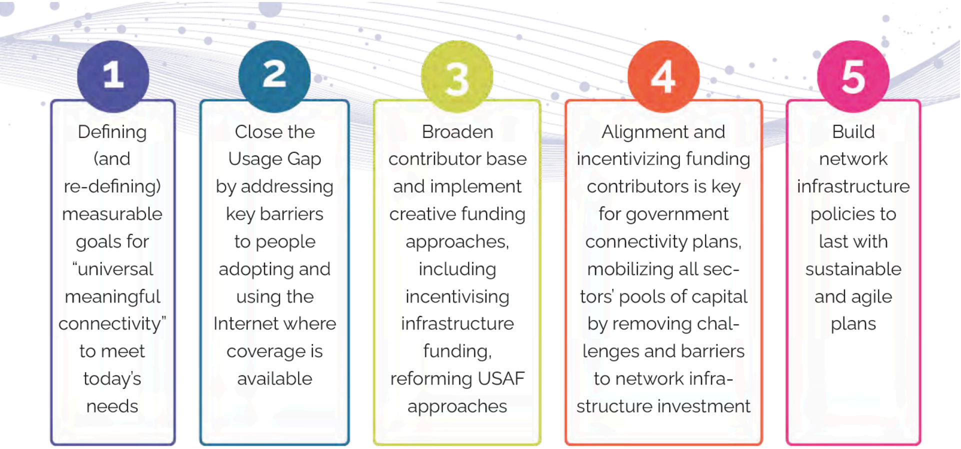
TARGET 5
INCREASE USE OF E-FINANCE

TARGET 6
GET MSMEs ONLINE

TARGET 7
BRIDGE THE GENDER DIGITAL DIVIDE

To learn more about the Broadband Commission 2025 Advocacy Targets, visit broadbandcommission.org/advocacy-targets/

2025 TARGETS BROADBAND COMMISSION



1 Defining (and re-defining) measurable goals for "universal meaningful connectivity" to meet today's needs

2 Close the Usage Gap by addressing key barriers to people adopting and using the Internet where coverage is available

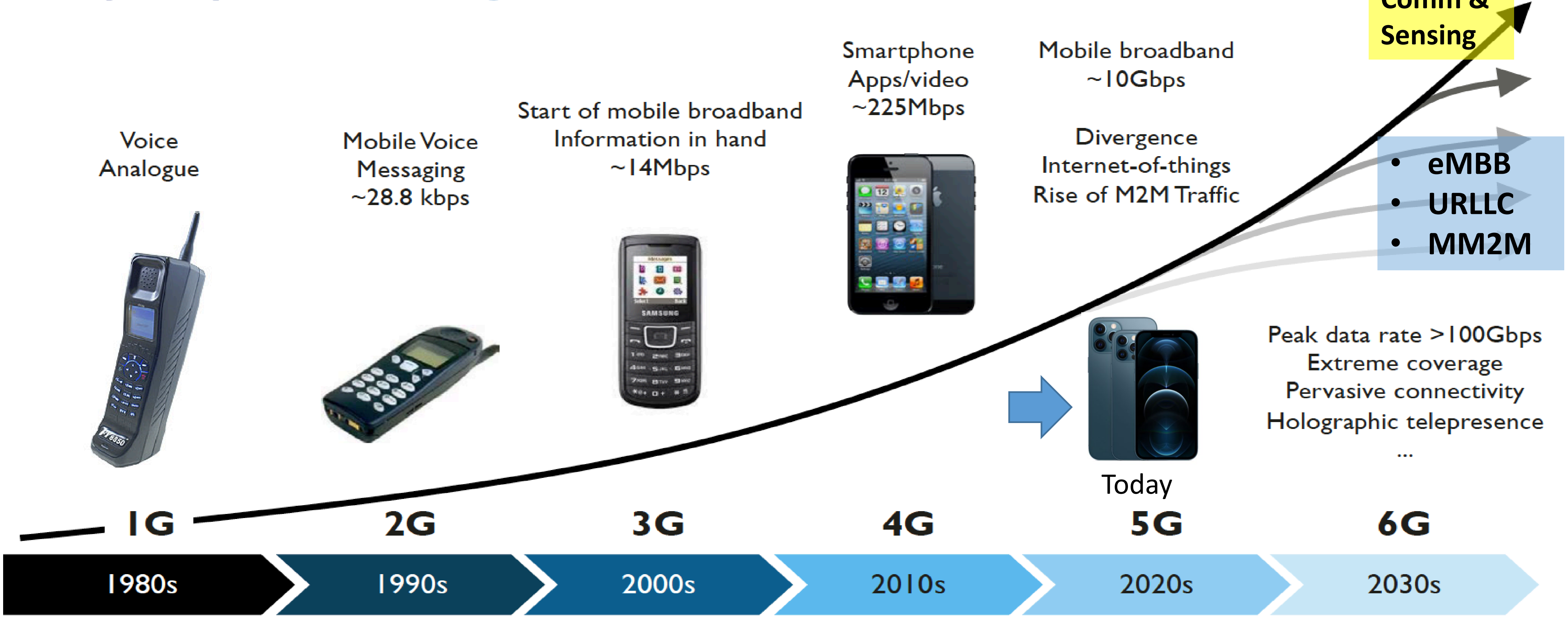
3 Broaden contributor base and implement creative funding approaches, including incentivising infrastructure funding, reforming USAF approaches

4 Alignment and incentivizing funding contributors is key for government connectivity plans, mobilizing all sectors' pools of capital by removing challenges and barriers to network infrastructure investment

5 Build network infrastructure policies to last with sustainable and agile plans

https://broadbandcommission.org/publication/state-of-broadband-2023/

Every 10 years a new generation of mobile communication



Voice
Analogue

Mobile Voice
Messaging
~28.8 kbps

Start of mobile broadband
Information in hand
~14Mbps

Smartphone
Apps/video
~225Mbps

Mobile broadband
~10Gbps

Divergence
Internet-of-things
Rise of M2M Traffic

Today

Peak data rate >100Gbps
Extreme coverage
Pervasive connectivity
Holographic telepresence
...

Joint Comm & Sensing

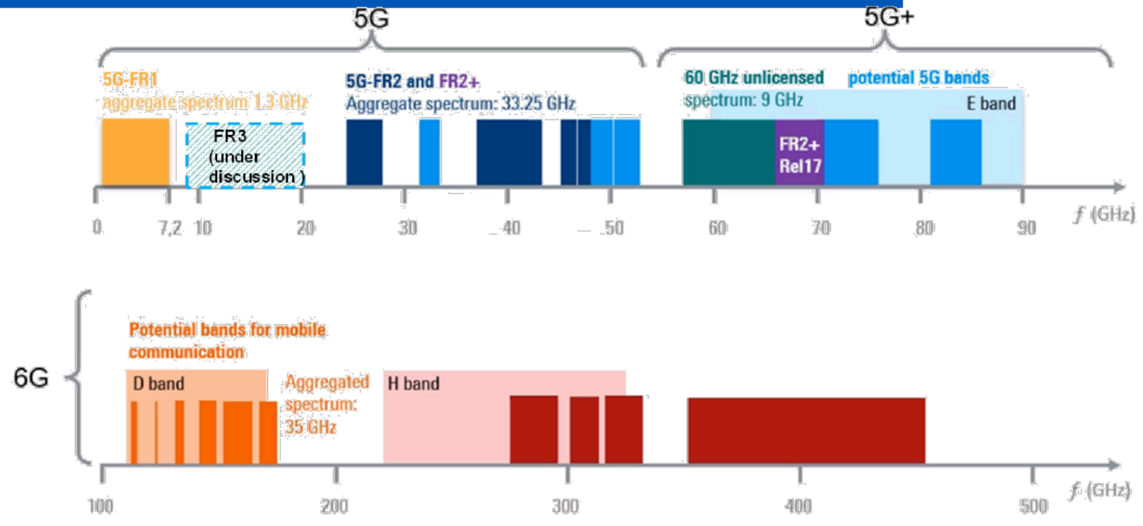
- **eMBB**
- **URLLC**
- **MM2M**

1G	2G	3G	4G	5G	6G
1980s	1990s	2000s	2010s	2020s	2030s

Nadine Collaert, imec, Emerging device and heterogenous integration technologies for sub-THz Applications, ISSCC 2022, 6G Forum.

IEEE
IEEE photonics Society
semi
IEEE Electronics Packaging Society
ASME
Electron Devices Society

Solutions needs to enable additional spectrum



Source: Taro Eichler, Millimeterwave and THz Technology for 5G and Beyond, Rohde & Schwarz

- Sweet Spot still C-Band
- FR2 bands usage limited but growing
- 6G …

☐ Congested licensed bands below 6GHz
  - ■ Best for range and transmission
  - ■ Over $1 Trillion in Value!

☐ Coexistence challenges with WiFi

☐ FR3 slowly progressing through unwinding exiting allocations

☐ US C-band auction: $80B for 280 MHz
  - ■ FR3 spectrum value will be large

☐ Huge amounts of spectrum available at 100-300 GHz
  - ■ Solutions will be technically challenging

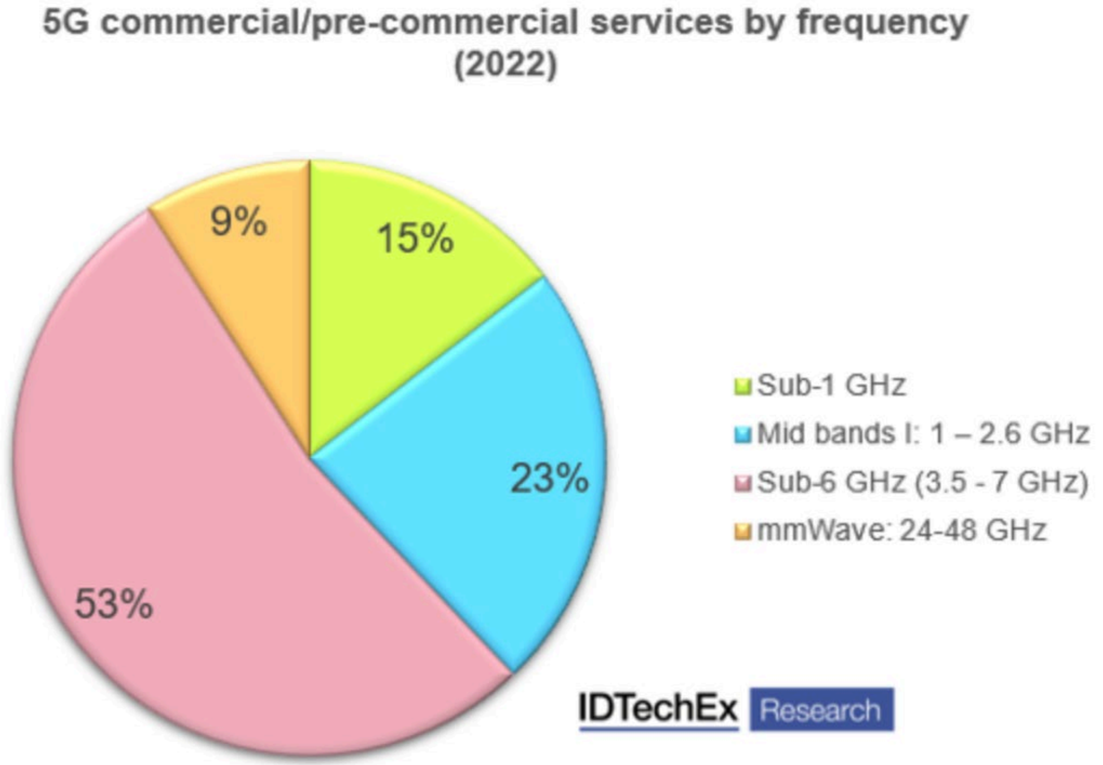
Nicholas Comfoltey, “Emerging Device Technologies for RF/mmWave FEMs,” ISSCC2023 Forum

MmWave Development in 2023: Where's It Going & What Are the Challenges

Positives:3 years after 5G was officially commercialized, while most of the deployments are primarily focused on 5G mid-band, the development of 5G mmWave technology has also been underway. 5G mmWave, operating in high-frequency bands between 24-100 GHz, offers faster data transfer rates, low latency, and higher bandwidth compared to the previous wireless technology.

Negatives: However, the deployment of 5G mmWave technology poses challenges beyond its physical characteristics, such as shorter range and susceptibility to interference.

- Lack of compelling business use cases that justify its cost and deployment challenges.
- The benefits may not be enough to justify the significant investment required to deploy it.
- Need to to identify and prioritize the use cases to provide the most significant impact and return on investment.


5G commercial/pre-commercial services by frequency (2022)

Source: "5G Market 2023-2033: Technology, Trends, Forecasts, Players" from IDTechEx

FR2: FWA and high-density areas like stadiums and airports

https://www.idtechex.com/en/research-article/mmwave-development-in-2023-wheres-it-going-and-what-are-the-challenges/29010

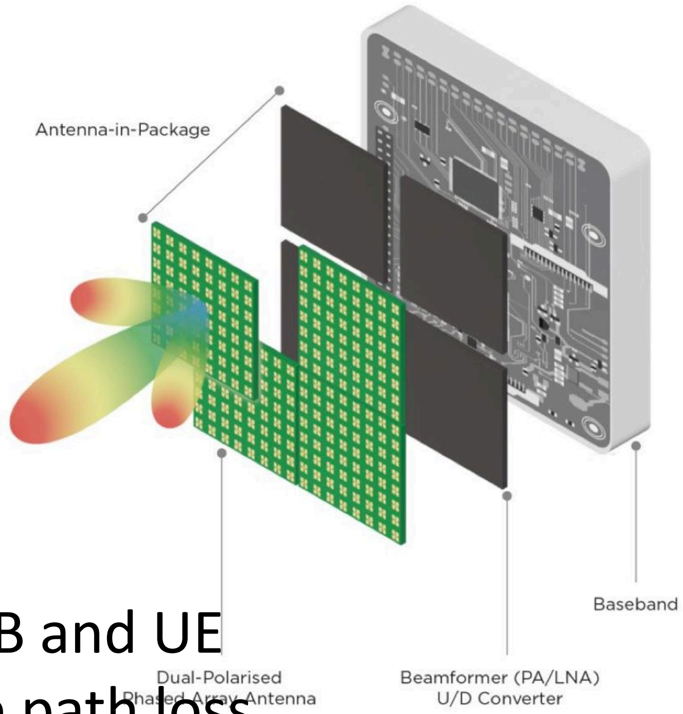
Millimeter-Waves Challenges and Mitigations

Challenges:

- Propagation: Line of Sight
- Rain attenuation
- Foliage attenuation
- Building penetration losses

Mitigations:

- Phased Arrays
- Use of low-band for UL
- Use of High Power UE

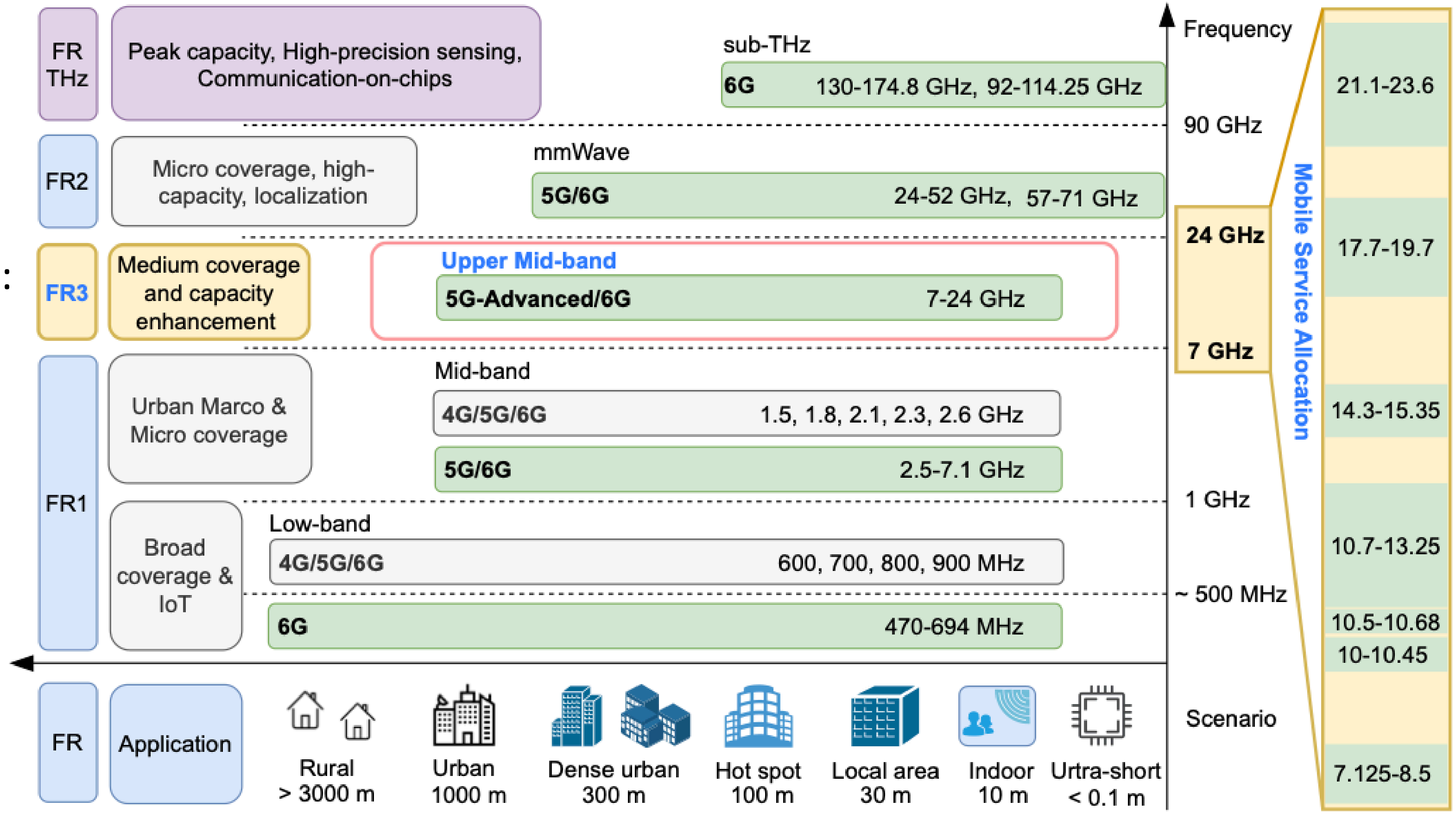


AiP (Antenna-in-Package) subsystem is designed for both gNB and UE to eliminate mmWave propagation loss as well as reduce the path loss from the antenna to the baseband to improve the receiving sensitivity.

https://www.gsma.com/futurenetworks/wp-content/uploads/2022/10/FINAL-5G-mmWave-Deployment-Best-Practices-Design-White-Paper-November-2022.pdf

6G Wireless Communications in 7–24 GHz Band: Opportunities, Techniques, and Challenges

Emergence of FR3:



FR THz	Peak capacity, High-precision sensing, Communication-on-chips	sub-THz	**6G**	130-174.8 GHz, 92-114.25 GHz
FR2	Micro coverage, high-capacity, localization	mmWave	**5G/6G**	24-52 GHz, 57-71 GHz
FR3	Medium coverage and capacity enhancement	**Upper Mid-band**	**5G-Advanced/6G**	7-24 GHz
FR1	Urban Marco & Micro coverage	Mid-band	**4G/5G/6G**	1.5, 1.8, 2.1, 2.3, 2.6 GHz
			5G/6G	2.5-7.1 GHz
	Broad coverage & IoT	Low-band	**4G/5G/6G**	600, 700, 800, 900 MHz
			6G	470-694 MHz

https://arxiv.org/pdf/2310.06425v1.pdf

Why mmWave?

Shannon-Hartley Theorem:

$$C = B\log_2\left(1+\overbrace{\frac{\bar{P}}{N_o B}}^{\text{SNR}}\right)$$

C: Channel capacity
B: Channel Bandwidth [Hz]
N_o: Noise Power Spectral Density [W/Hz]
P: Average Received Power [W]

High SNR: Capacity is linear in bandwidth, logarithmic in power.

Low SNR: Capacity is insensitive to bandwidth, linear in power.

Carrier Frequency	Modulation	Available Bandwidth[GHz]	Max Data Rate [Gb/s]
Sub-6GHz	4096-QAM	0.15	1.35
28GHz	256-QAM	0.85	5.1
60GHz	64-QAM	8.64	38.9
70GHz	64-QAM	5	22.5

~30x increase in data rate!

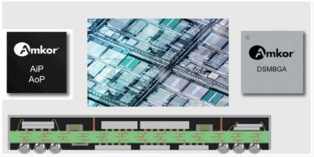
Operation at mmWave frequencies enables wide bandwidth designs → Potential for higher data rates

RF Front-Ends Play a Critical Role to the Deployment of 5G Ecosystem (RFICs, Antennas and Advanced Packaging)

According to the Fact & Figures research report, the global 5G Smart Antenna Market in 2019 was approximately USD 260 million. The market is expected to grow at a CAGR of 57% and is anticipated to reach around USD 6,325 million by 2026.

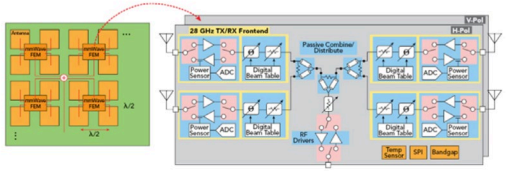
- ***UE is highly SWaP-C constrained***
  - ***Battery Life***
  - ***Mm-wave propagation losses***
- ***BS Challenges***
  - ***Signal Blockage***
  - ***Output Power & PAE***
  - ***Thermal***
  - ***Yield & Affordability***
- ***Key Technologies:***
  - ***Advanced node CMOS, FD-SOI***
  - ***2.5D/3D packaging***
  - ***Low-loss substrates***

5G RF Front-End Modules faces many design challenges



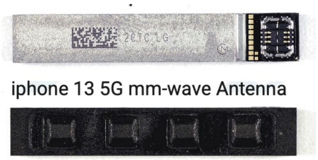
AiP / AoP Modules (Amkor)

https://www.everythingrf.com/news/details/12962-amkor-develops-advanced-packaging-technology-for-5g-rf-front-end-modules



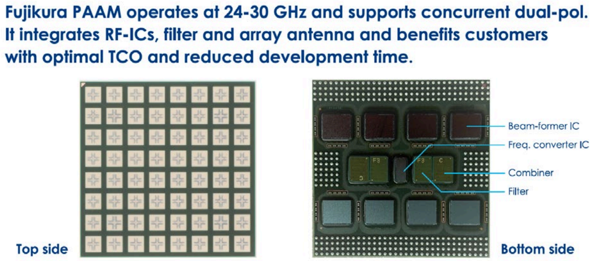
Si/SiGe Beamformers (GF)

https://www.globalfoundries.com/sites/default/files/rf_soi_can_save_billions_in_5g_mmwave_network_costs_with_efficient_pas_2020-04-06_microwave_journal.pdf



iphone 13 5G mm-wave Antenna

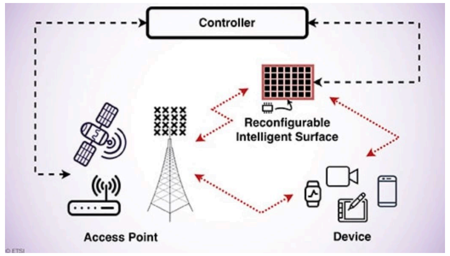
https://unitedlex.com/insights/apple-iphone-13-pro-max-teardown-report



Fujikura PAAM operates at 24-30 GHz and supports concurrent dual-pol. It integrates RF-ICs, filter and array antenna and benefits customers with optimal TCO and reduced development time.

Mm-wave BS Phased Array – Beamformer Technologies using III-V and SiGe (Fujikura)

https://mmwavetech.fujikura.jp/5g/?gclid=EAIaIQobChMI4qWzsLLs8wIVGmxvBB0EhwfOEAAYAyAAEgJ96_D_BwE

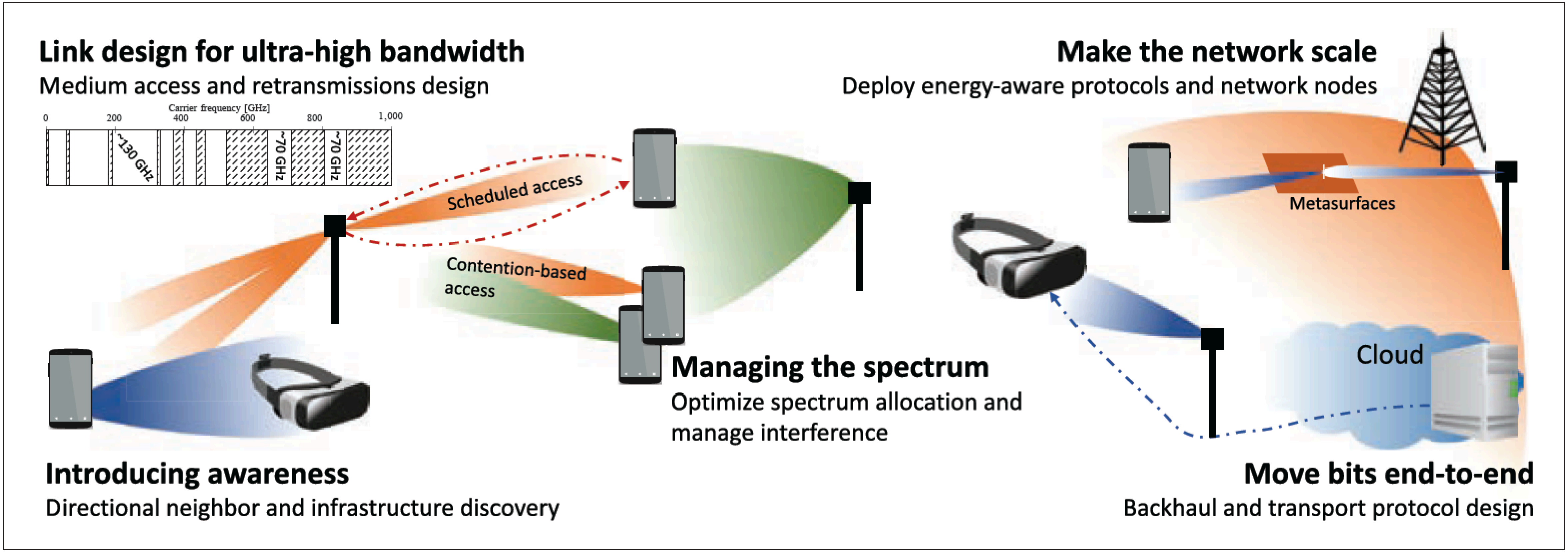


Intelligent Reflective Surfaces for 6G (ETSI)

https://www.5gtechnologyworld.com/etsi-launches-intelligent-surfaces-effort/

Resilient 5G

Main Design Challenges for End-to-End, Full-Stack THz Networks



Link design for ultra-high bandwidth
Medium access and retransmissions design

Make the network scale
Deploy energy-aware protocols and network nodes

Managing the spectrum
Optimize spectrum allocation and manage interference

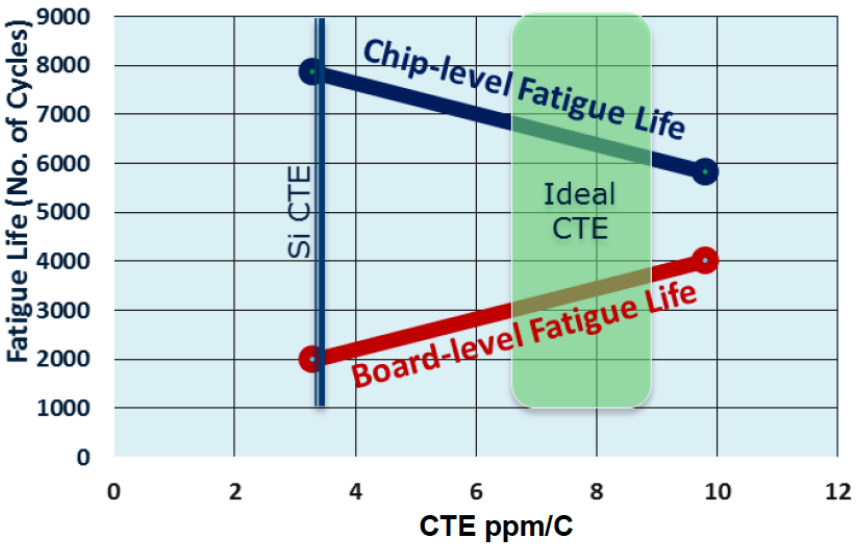
Introducing awareness
Directional neighbor and infrastructure discovery

Move bits end-to-end
Backhaul and transport protocol design

M. Polese, “Toward End-to-End, Full-Stack 6G Terahertz Networks,” IEEE Communications Magazine, Nov 2020. (Northeastern University)

Heterogeneous Integration Platform

Substrate Core	Silicon	Organic		Glass
		Laminates	Fanout (Epoxy Mold Compound)	
Material properties				
Surface roughness (nm)	<10	400-600	> 1000	<10
CTE (ppm/K)	2.9-4	3-17	16-30	3-9
Young's modulus (GPa)	165	10-40	22	50-90
Moisture absorption	0	0.04%	1-2.5%	0
Thermal conductivity (W/m.K)	148	0.9	0.5-0.75	1.1
Physical Dimensions				
Package size (mm)	35x35	70x70	50x50	100x100
Panel/Wafer size	300 mm	710 mm^2	300 mm / 510 mm^2	710 mm^2

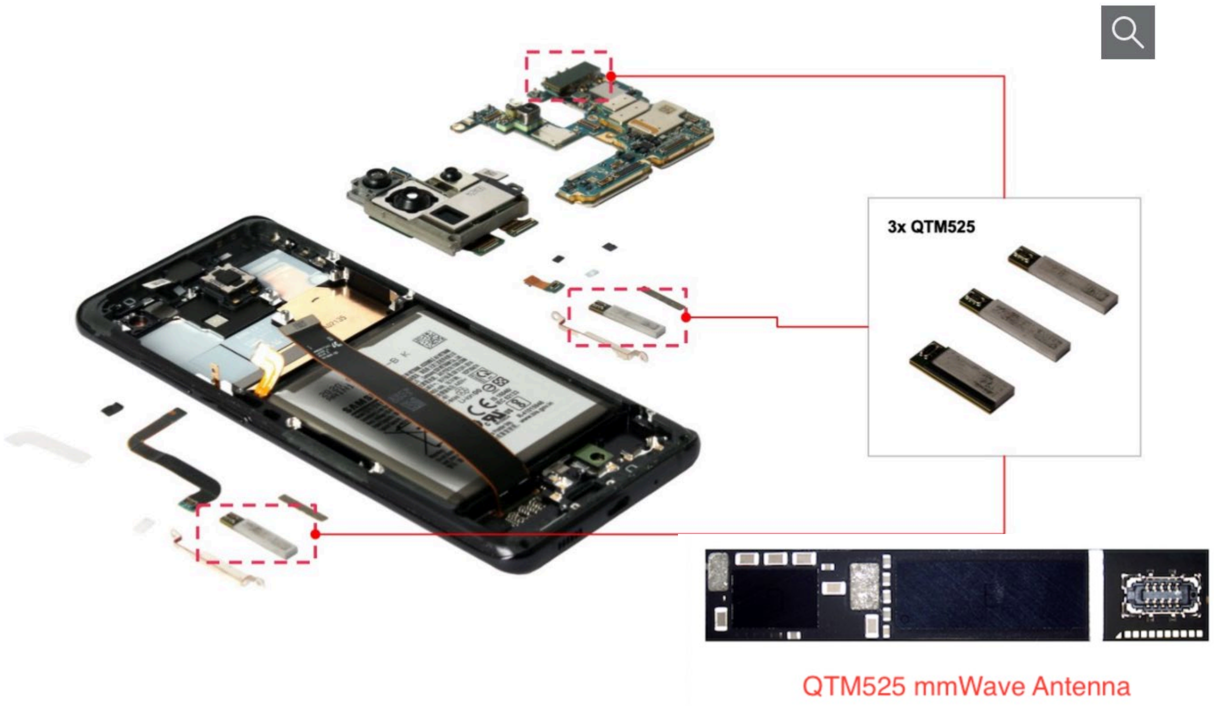


- ❑ Materials with Silicon like properties that maximize chip and board level reliability and support larger body sizes required!
- ❑ CTE in the range of 7-9 ppm/C with low surface roughness, Young's Modulus and zero moisture absorption required.
- ❑ Glass Interposer is a good candidate!

Madhavan Swaminathan, "Packaging for mmWave Communications," March 2021, INEMI Webinar

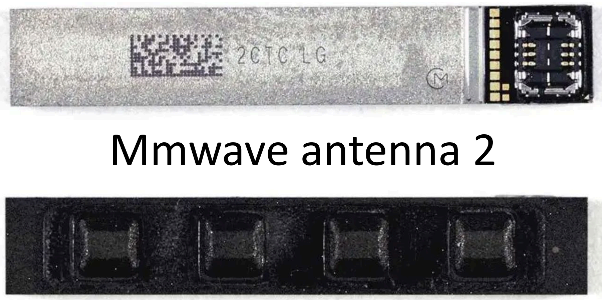
Mm-wave Phased Arrays: a Common Feature in your Phone!

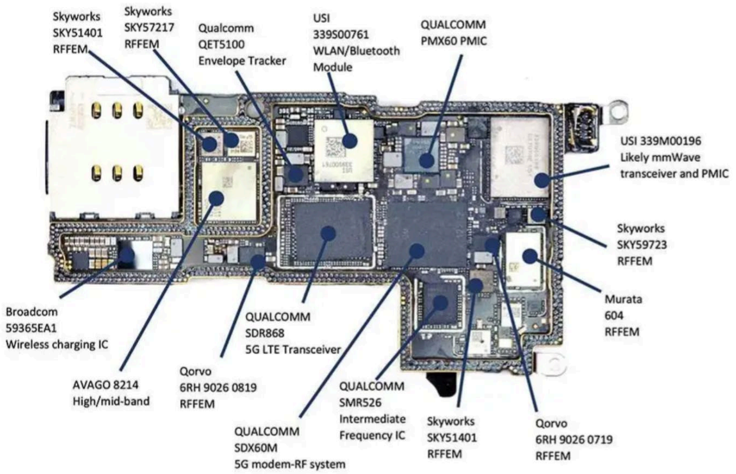
5G Antenna Modules in Samsung S20 Ultra



https://omdia.tech.informa.com/OM006104/Criticality-of-5G-Modem-to-RF-Integration-A-look-inside-Samsung-Galaxy-S20-Ultra

Iphone 13 Pro mm-wave modules / antenna and 5G Modem

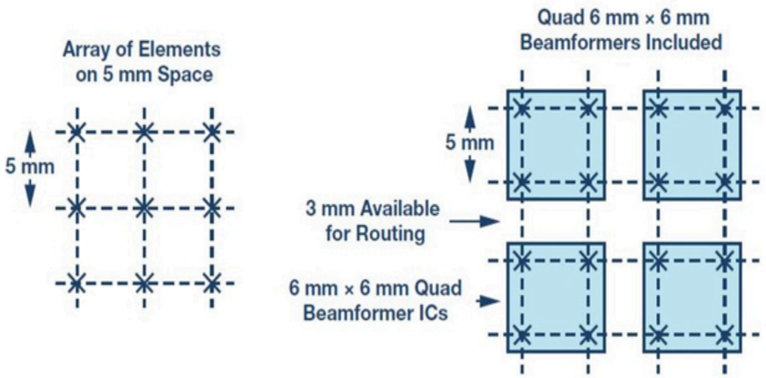




https://unitedlex.com/insights/apple-iphone-13-pro-max-teardown-report/

Technology/Capability Gaps and Showstoppers

Challenge 1: Tight Integration is Needed for mm-wave Phased Arrays



- At 30 GHz, $\lambda/2$ = 200 mils, or 5 mm
- Electronics Footprint a Serious Challenge
  - Worse for Dual Pole
- Front-End Function Desired in Beamformer Package
  - PAs and LNAs

Frequency	Element Spacing	Dual Pole I/O Spacing
3 GHz	50 mm, 2 inches	25 mm, 1 inch
10 GHz	15 mm, 600 mils	7.5 mm, 300 mils
30 GHz	5 mm, 200 mils	2.5 mm, 100 mils

6G ➡ 140 GHz 1mm

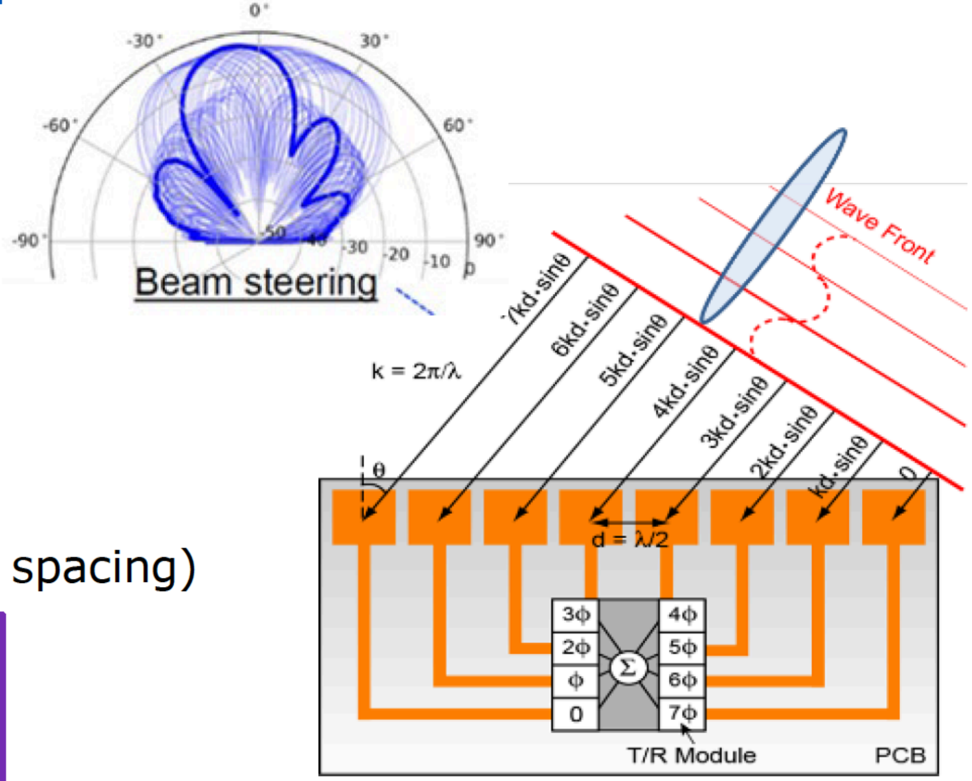
5G Front-End architecture (number of elements, EIRP, Si vs III-V, and Packaging) need to be tailored for each use case

Phased Arrays are a key enabler for mmWave

- Link budget improves 30*log*10(N)
- For a phased array of N elements
  - Tx array: focused Tx radiation energy
    - TRP increases by $10\log_{10}(N)$
    - EIRP increases by $20\log_{10}(N)$
  - Rx array: enhanced Rx sensitivity
    - S/N increases $10\log_{10}(N)$
    - NF decreases by $10\log_{10}(N)$
- Beam width narrows ~ $2*\sin^{-1}(2/N)$
- Array area decreases $(l/2)^2$ (l/2 lattice spacing)

Lower Tx power per Power Amplifier and Antenna element

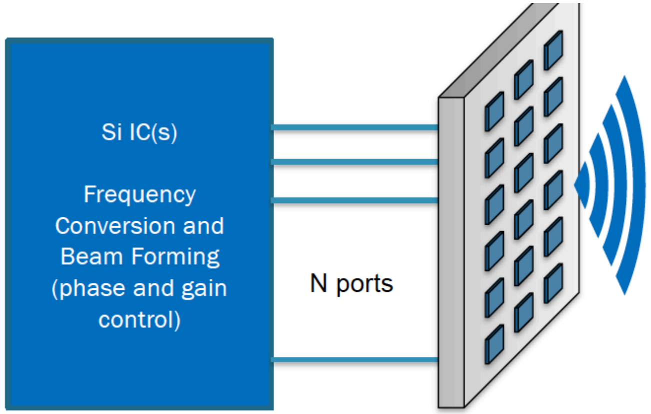
mmWave FEM requirements can be addressed by Silicon technologies

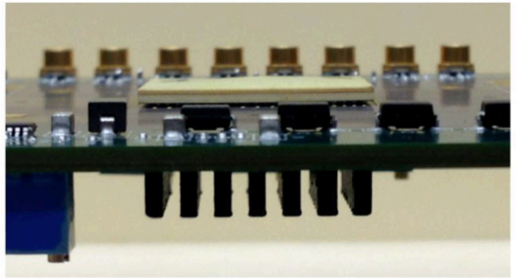


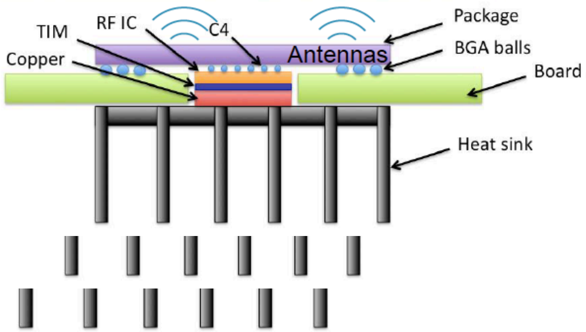
Gabriel Rebeiz, "Si RF Technologies Enabling 5G Millimeter Wave Applications," October 2018.

Nicholas Comfoltey, "Emerging Device Technologies for RF/mmWave FEMs," ISSCC2023 Forum

Key Antenna Package Requirements







Electrical

- Impedance matching at each port
- Radiate EM energy efficiently
- Achieve low coupling between antenna elements
- Have equal signal delays between input ports and antenna feedlines
- Achieve near hemi-spherical radiation patterns, equal among radiation elements
- Feature sufficient layers for IC interconnects

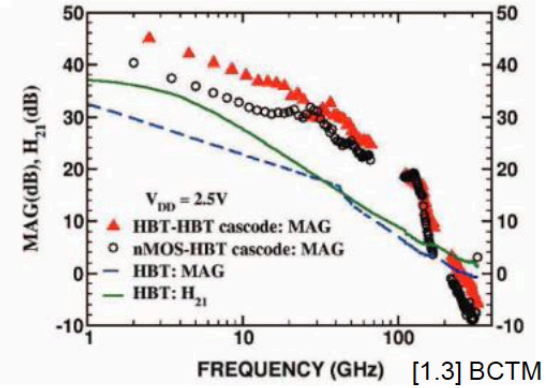
Thermomechanical

- Provide mechanical support to the ICs
- Achieve low CTE mismatch with the ICs for mechanical stability over temperature
- Reliable mechanical connection to ICs and boards

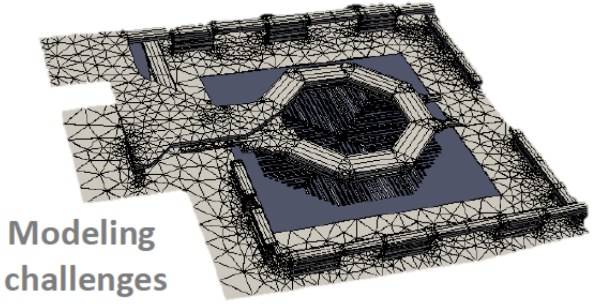
Bodhisatwa Sadhu, Alberto Valdes-Garcia, “Silicon based millimeter Wave Phased Array Design,” IMS2020 Technical Lecture

Challenges for Millimeter-Wave Design

1. IC design & modeling is difficult

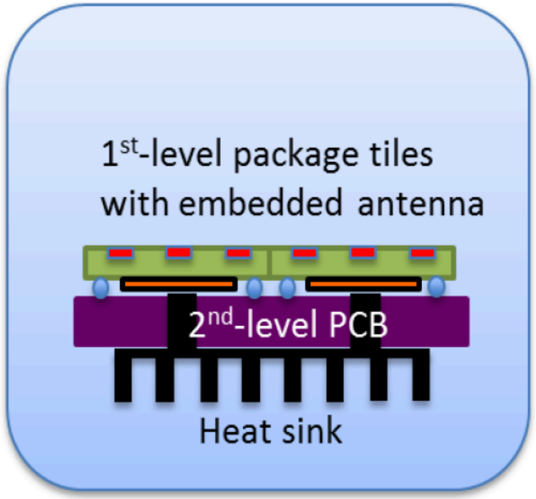


[1.3] BCTM 2015



Modeling challenges

2. Antenna-package-IC integration is difficult



Integration challenges: Antenna constrained by package, package constrained by IC & thermal

3. Measurements are difficult

Requires expensive specialized equipment and frequent calibration

Bodhisatwa Sadhu, Alberto Valdes-Garcia, "Silicon based millimeter Wave Phased Array Design," IMS2020 Technical Lecture

Substrate and Process Options

LTCC (Ceramic)

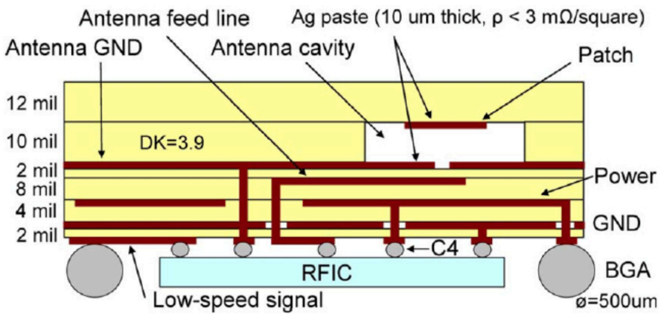


Image courtesy: IBM

LCP-based MLO (Organic)

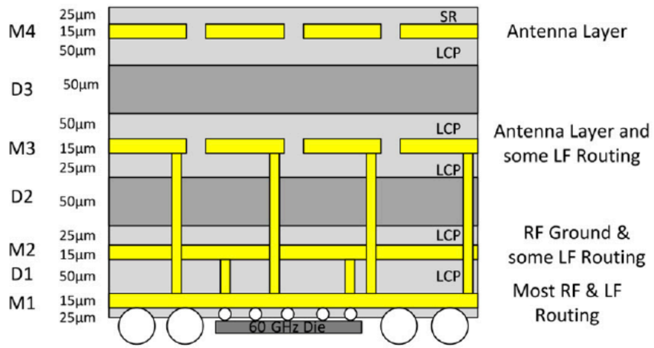


Image courtesy: IBM

PCB

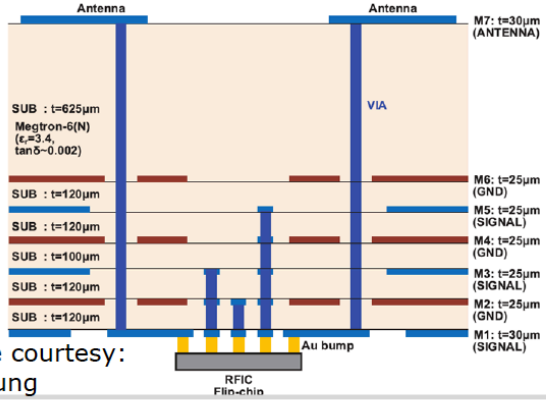


Image courtesy: Samsung

Wafer-level packaging

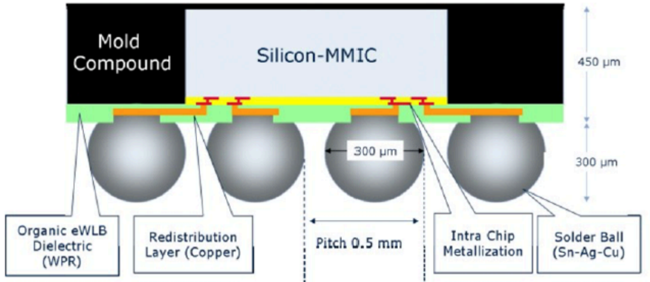


Image courtesy: Infineon

Note: antennas on separate substrate, not shown

Thin films on glass

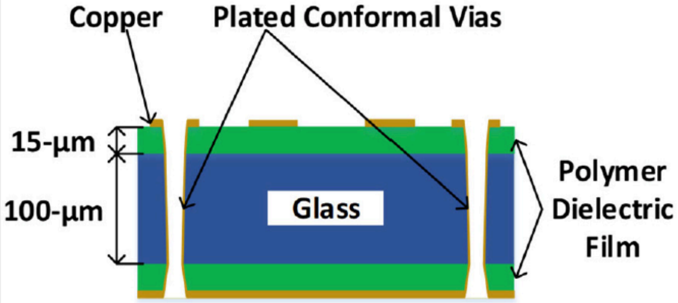


Image courtesy: Georgia Tech

Quartz Superstrate

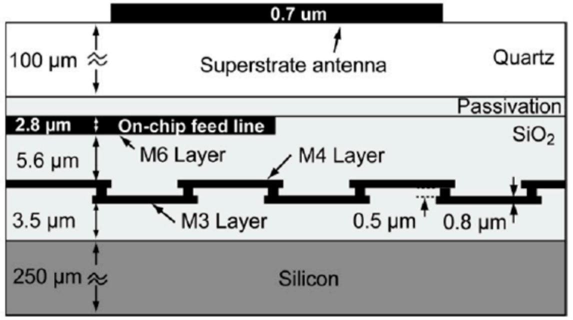


Image courtesy: UCSD

[18] JMW 2021

Note that these examples are not necessarily the pioneers of these package technologies for mmWave phased arrays.

Examples of Advanced Packaging Techniques for 5G

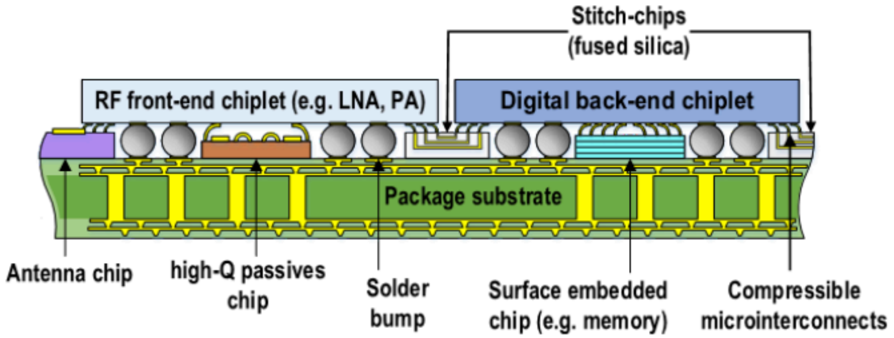


Fig. 1. Envisioned polylithic integration using stitch-chips for RF/mm-wave applications

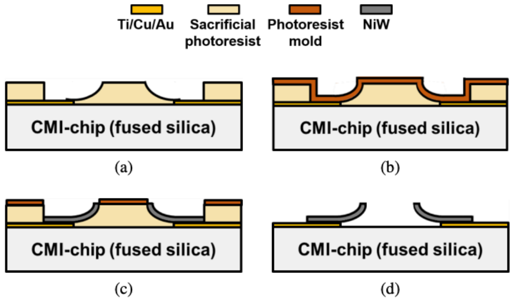


Fig. 4. CMI-chip fabrication process: (a) photoresist patterning after pac lift-off, (b) photoresist spray coating after seed layer sputtering, (c) photoresis molding and electroplating, and (d) CMI releasing

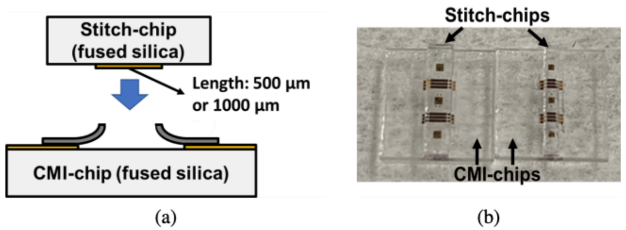
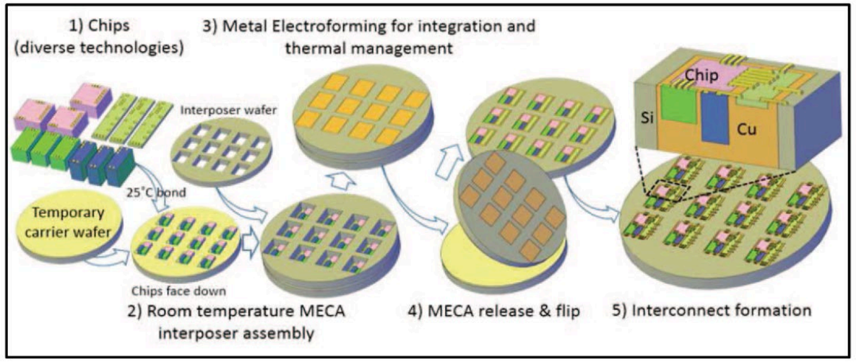
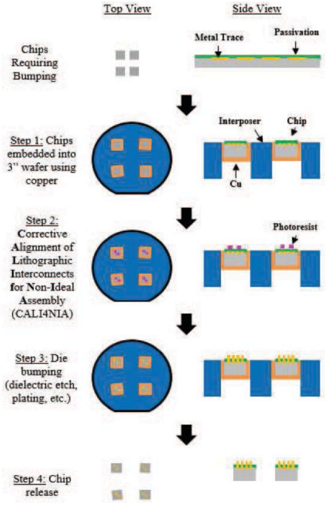


Fig. 5. Assembly: (a) flip-chip bonding of the stitch-chip and the CMI-chip and (b) samples after assembly

GaTech: 0.2dB Insertion Loss @ 28 GHz!

T. Zheng, "Polylithic Integration for RF/MM-Wave Chiplets using Stitch-Chips: Modeling, Fabrication, and Characterization," IMS2020, https://ieeexplore.ieee.org/document/9223887





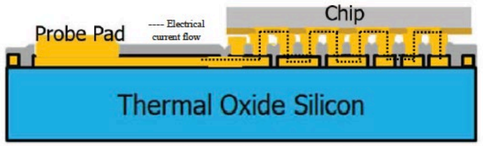


Fig. 10. Cartoon cross section diagram illustrating the daisy chain electrical connection between chip and fanout after bonding

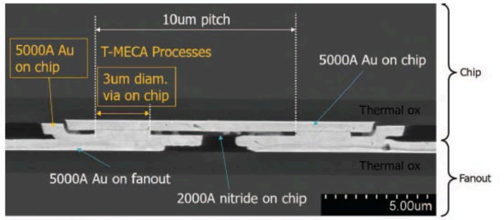


Fig. 11. SEM cross section image of two chip-fanout connection pairs showing the Au-Au bonding interface

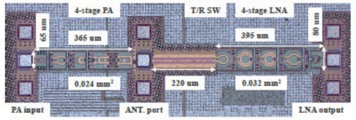
HRL: Wafer-Level integration for III-V

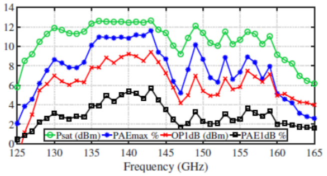
S. Nadre, "10um Pitch Bumping of Singulated Die Using a Temporary Metal Embedded Chip Assembly Process," 2022 ECTC

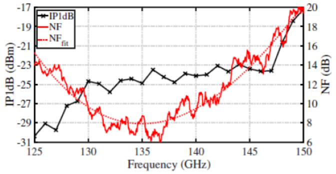
Highly Integrated D-Band Phased-Arrays for 6G wireless Communications

A 140 GHz FEM in 22nm FD-SOI imec

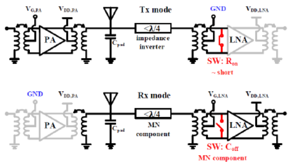
- ☐ Design
  - 4-stage PA, LNA
  - Asymmetric T/R Switch with T/L
  - ESD robustness
  - Stacked-FET PA
  - Gain boosting technique
  - Backgate terminated with 15KW R to enhance linearity and PAE
- ☐ Results (including switch loss)
  - Tx:
    33.6 dB Gain, 12.5 dBm Psat,
    10.8% PAE max
  - Rx:
    20 dB Gain, 9.2 dB NF, 20mW



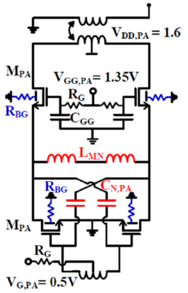




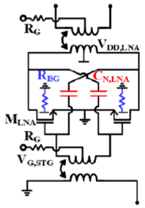
T/R switch schematic



PA output stage schematic



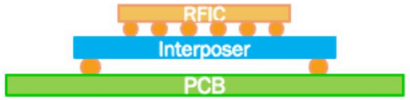
LNA schematic (1 of 4 stages)

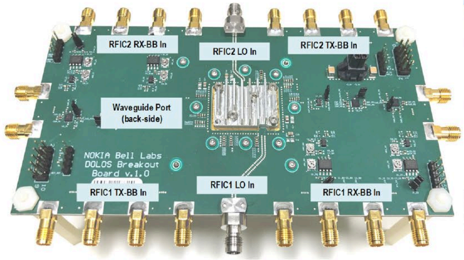


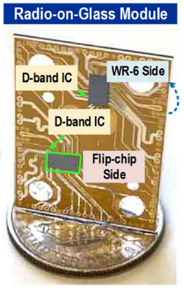
X. Tang et al," A 140 GHz T/R Front-End Module in 22 nm FD-SOI CMOS ", RFIC 2021

Radio-On-Glass Technology Nokia

- ☐ Glass is used as an interposer
- ☐ Carrier DC, digital and RF
- ☐ integrated SIW waveguide
  - Low loss (0.04 dB/mm)
  - Conversion from GSG to SI
  - SIW to WR-6 conversion
- ☐ PCB carries baseband interface
- ☐ LO interface for both chips





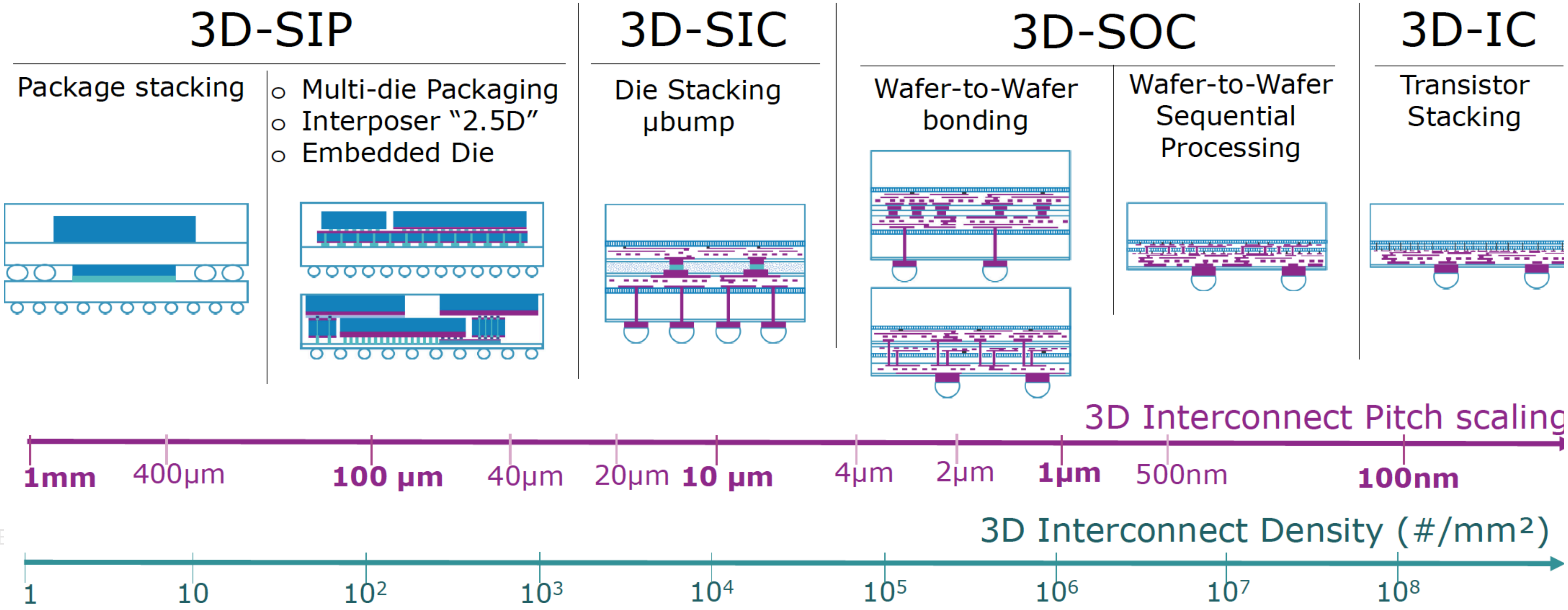


X. Tang, “A 140 GHz T/R Front-End Module in 22 nm FD-SOI CMOS, RFIC 2021,RFIC2021

Mohamed Elkhouly, Shahriar Shahramian, Nokia: ISSCC 2022, 6G Forum

What is the breakpoint for AiP versus AoC? And for 2.5D versus 3D?

The 3D Interconnect Technology Landscape



3D-SIP

Package stacking

- Multi-die Packaging
- Interposer "2.5D"
- Embedded Die

3D-SIC

Die Stacking
µbump

3D-SOC

Wafer-to-Wafer bonding

Wafer-to-Wafer Sequential Processing

3D-IC

Transistor Stacking

3D Interconnect Pitch scaling

1mm 400µm **100 µm** 40µm 20µm **10 µm** 4µm 2µm **1µm** 500nm **100nm**

3D Interconnect Density (#/mm²)

1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8

Nadine Collaert, imec, Emerging device and heterogenous integration technologies for sub-THz Applications, ISSCC 2022, 6G Forum.

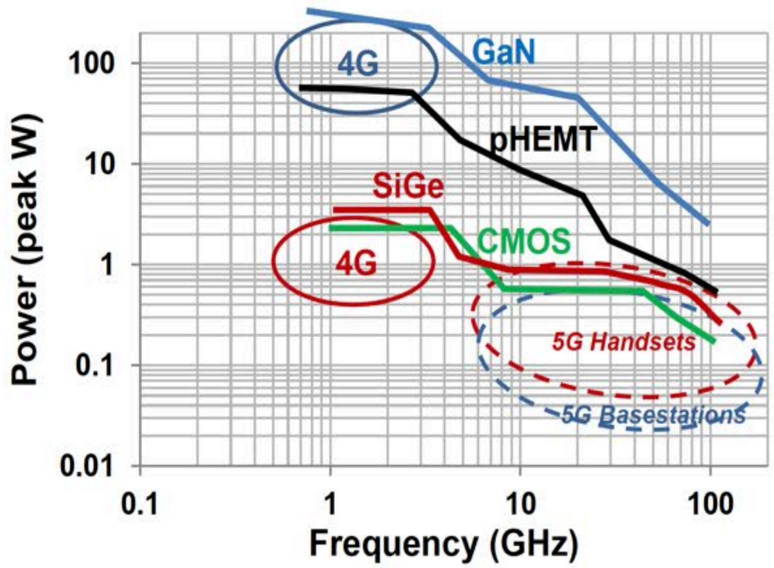
Technology/Capability Gaps and Showstoppers

Challenge 2: Selection of Semiconductor Technology Based on Output Level

5G Application Scenarios & Requirements 2018 (estimated)

	Handset	Access point	Base station	Backhaul	Last mile
EIRP (ave)	30 dBm	43dBm	60dBm	60dBm	75 dBm
Number antennas	4-6	32	256	256	256
Pave / PA	14dBm	11dBm	10dBm	10dBm	25dBm
Pmax/PA	23dBm	20dBm	19dBm	19dBm	33dBm
Efficiency (ave)	20%	20%	20%	20%	20%
DC power	0.6W	2W	12W	12W	390W

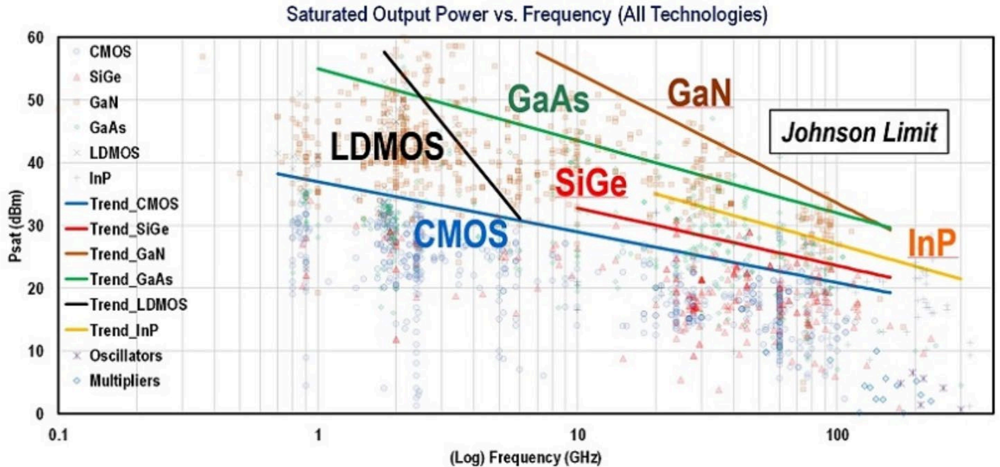
Estimated Power Ranges for 5G TX ICs & *Estimated* Max Power of Different Technologies



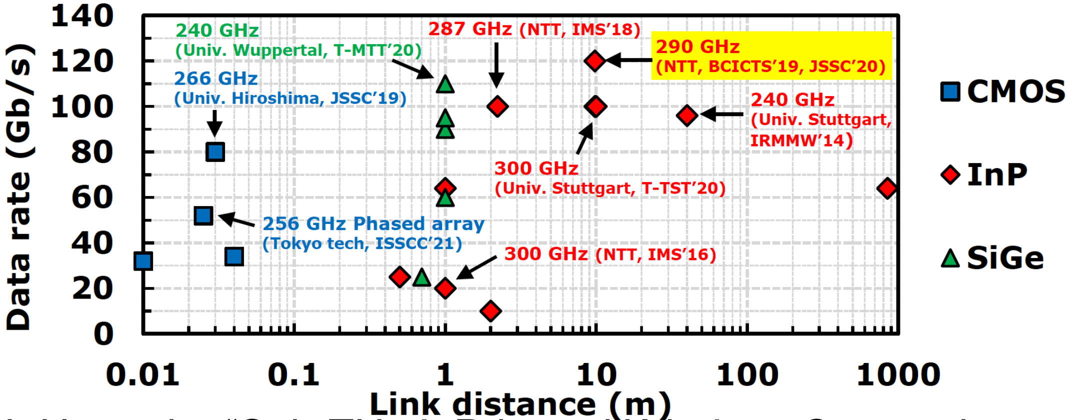
Necessary Semiconductor Technologies for 6G

- Objective
  - Support high data rate Communications
  - Spatial multiplexing for high capacity
- Benefits (140 – 1000 GHz)
  - Large available spectrum
  - Shorter wavelength – more channels for same sized array
- Challenge
  - Atmospheric attenuation
  - PAA element spacing - –λ/2 @ 150 GHz is 1 mm
  - Challenging packaging technologies
- Technologies

  III-V: **InP HBT**, InP HEMT, GaN HEMT, SiGe
  - Heterogeneous Integration
  - Small Form Factor
  - Antenna On Chip



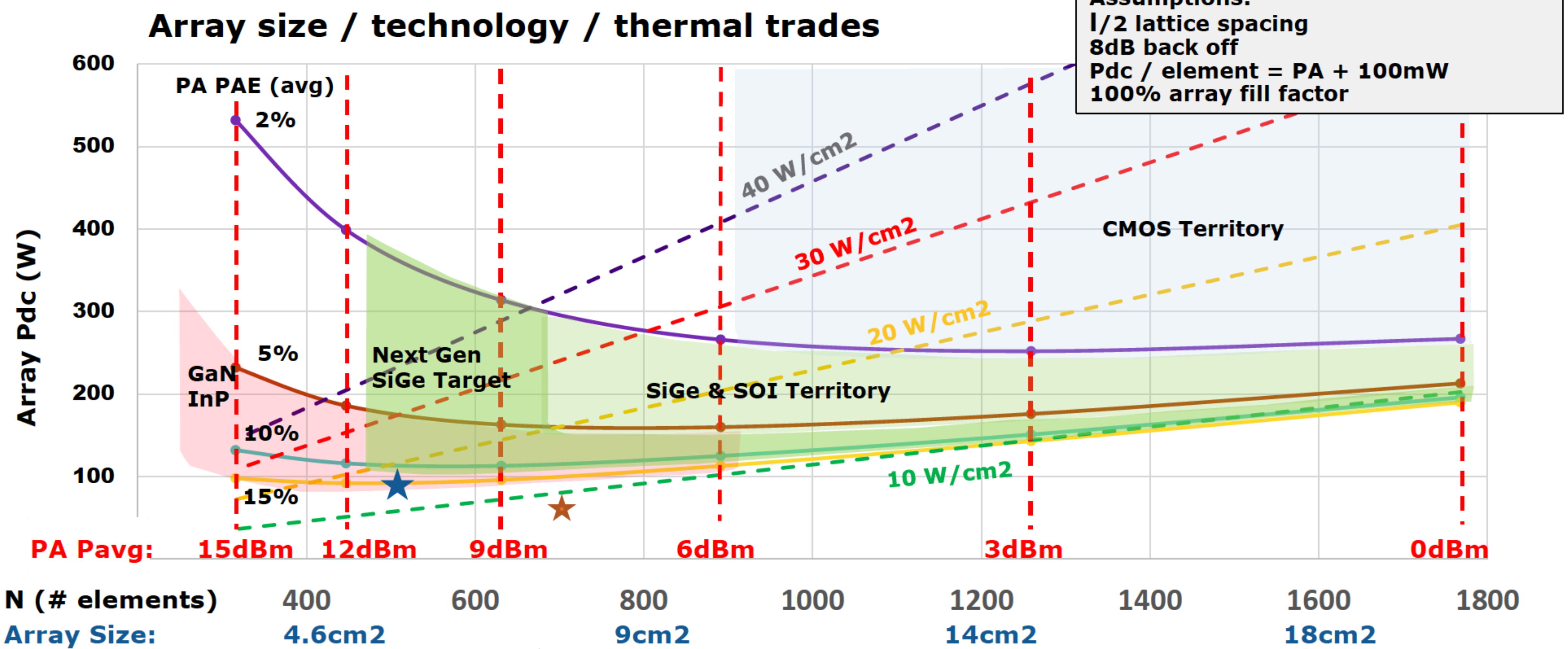
https://ideas.ethz.ch/research/surveys/pa-survey.html



H. Hamada, "Sub-THz InP-based Wireless Connection Techniques toward 6G, " ISSCC 2022, 6G Forum

140GHz Tx Analysis -- 65dBm EIRP Array PAE Contours

Assumptions:
l/2 lattice spacing
8dB back off
Pdc / element = PA + 100mW
100% array fill factor



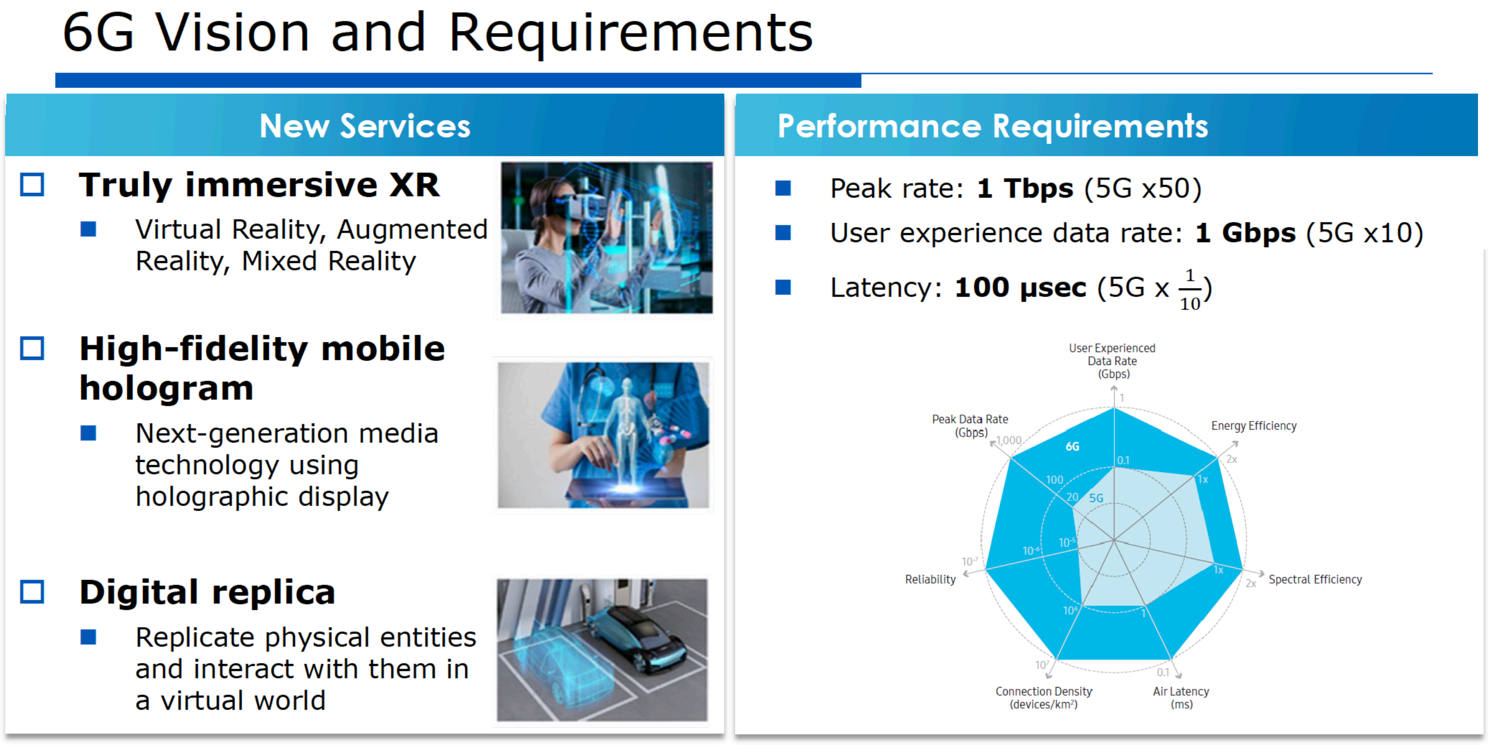
★ **90GHz 384-element IC area**
S. Shahramian et al

★ **28GHz 256-element BF IC area**
A. Khalil et al

28GHz 256-element →
Array size

Nicholas Comfoltey, “Emerging Device Technologies for RF/mmWave FEMs,” ISSCC2023 Forum

Next Stop For R&D: 6G



6G Vision and Requirements

New Services

☐ **Truly immersive XR**
- Virtual Reality, Augmented Reality, Mixed Reality

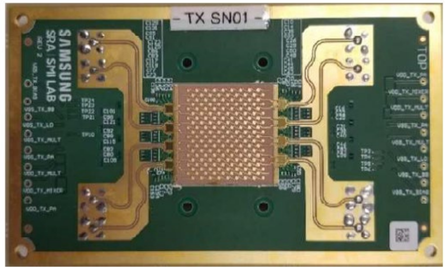
☐ **High-fidelity mobile hologram**
- Next-generation media technology using holographic display

☐ **Digital replica**
- Replicate physical entities and interact with them in a virtual world

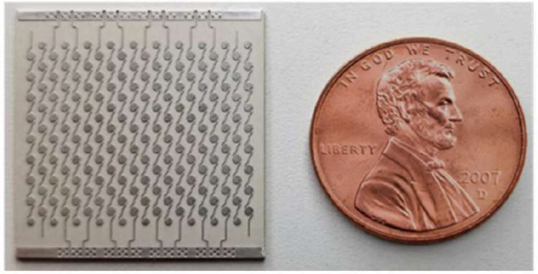
Performance Requirements

- Peak rate: **1 Tbps** (5G x50)
- User experience data rate: **1 Gbps** (5G x10)
- Latency: **100 μsec** (5G x $\frac{1}{10}$)

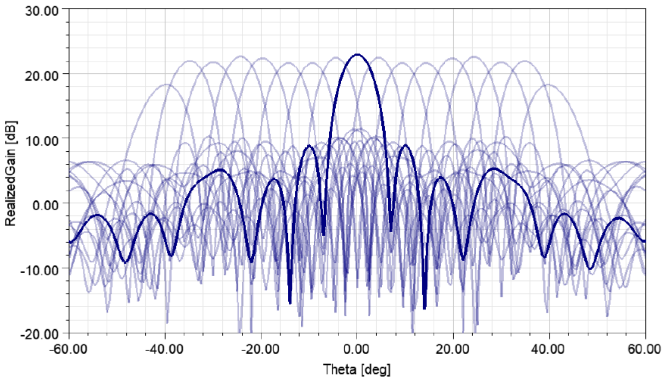
Gary Xu: THz for 6G Communications: Vision and Challenges, ISSCC2022 6G Forum



144 GHz TX beamformer module with eight dual-channel 45nm RFICs wire bounded to the antenna array. (Samsung)



Antenna array with 16 RF channels at 144 GHz carrier frequency.



Antenna pattern shows 21 dB of realized gain and +/-40 degree steerability.

Shadi Abu-Surra et al, ”End-to-end 140 GHz Wireless Link Demonstration with Fully-Digital Beamformed System, “ 2021 IEEE ICC Workshop” Samsung . UCSB

Foundational research Vision forming Service requirements Study Item (proposals) Work Item Trials IoDTs

Rel-21

6G

3GPP 6G Workshop

Rel-20

Next technology leap for new capabilities and efficiencies

Rel-20

Rel-19

Rel-18

Continued 5G evolution in the 6G era

5G Advanced

2^{nd} wave of 5G innovations

Rel-17

Rel-16

Rel-15

5G

A unified platform for innovations

Promise of 5G

5G

5G will expand the mobile ecosystem to new industries

Powering the digital economy

$13.1 Trillion

in global sales activities by 2035

Precision agriculture

Construction and mining

Digitized education

Connected healthcare

Richer mobile experiences

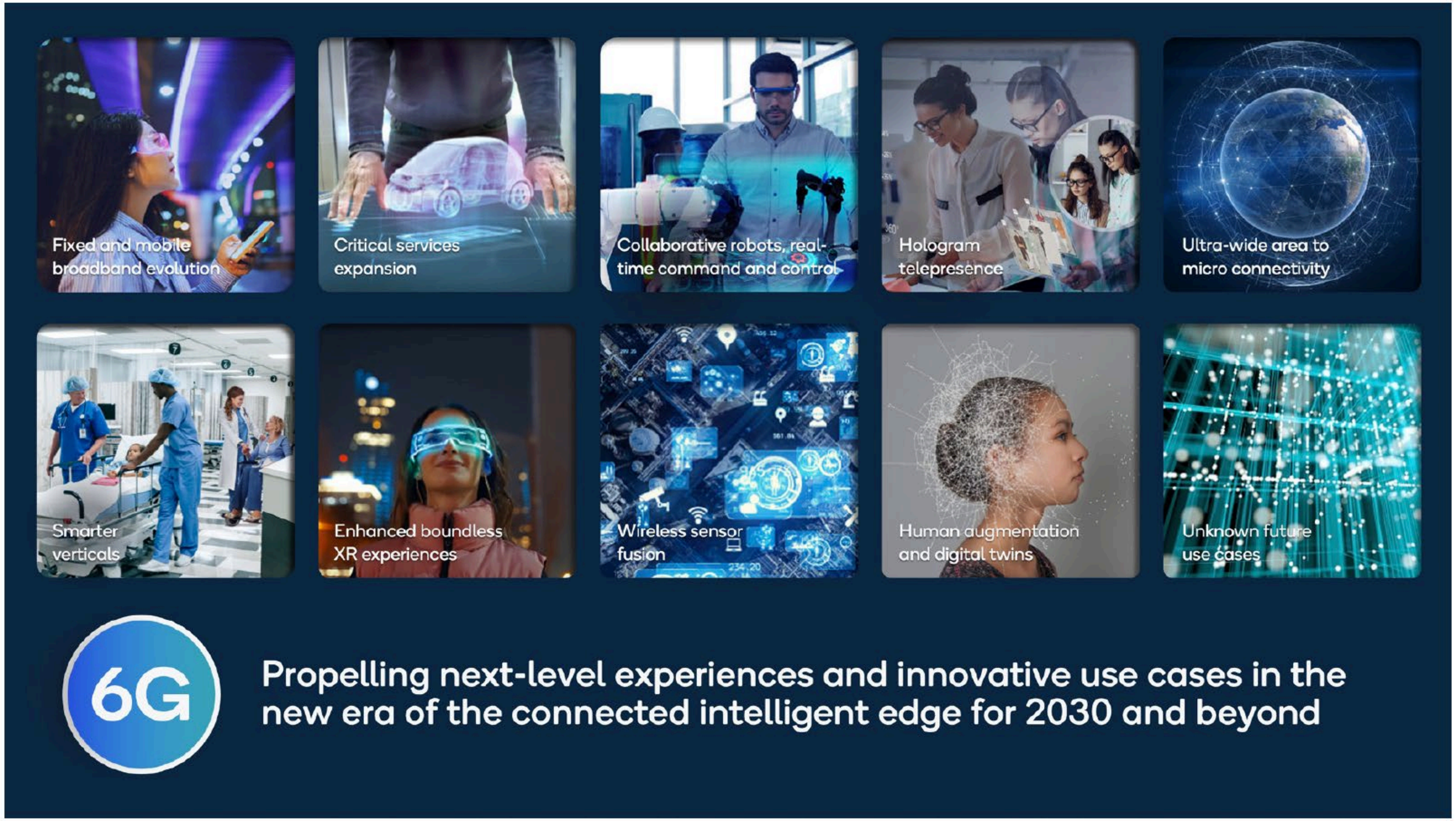
Smart manufacturing

Intelligent retail

Smart city

https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/Qualcomm-Whitepaper-Vision-market-drivers-and-research-directions-on-the-path-to-6G.pdf

6G will bring new and enhanced user experiences across the connected intelligent edge



Fixed and mobile broadband evolution

Critical services expansion

Collaborative robots, real-time command and control

Hologram telepresence

Ultra-wide area to micro connectivity

Smarter verticals

Enhanced boundless XR experiences

Wireless sensor fusion

Human augmentation and digital twins

Unknown future use cases

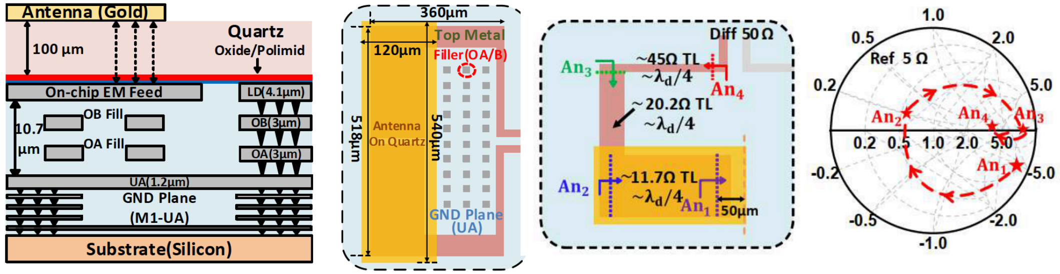
6G

Propelling next-level experiences and innovative use cases in the new era of the connected intelligent edge for 2030 and beyond

https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/Qualcomm-Whitepaper-Vision-market-drivers-and-research-directions-on-the-path-to-6G.pdf

6G 140-GHz Phased Array

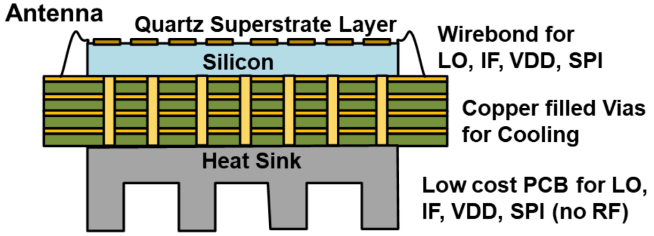
IMS Antenna on Quartz Superstrate



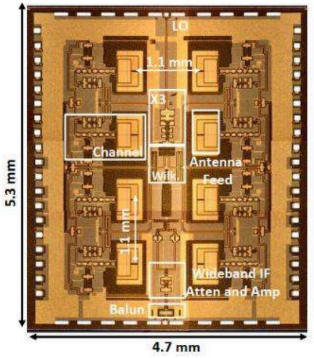
- Patch antenna arrays fabricated on the quartz superstrate
- EM wave coupled between the on-chip feed and the antenna
- Antenna feed matching network based on microstrip TL

IMS Build Phased-Array Systems at 140 GHz

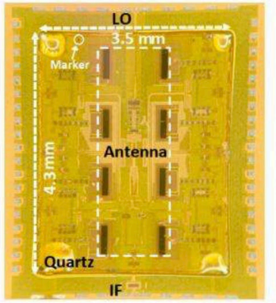
Method : Wafer-Scale with Quartz Superstrate
(Used above 60GHz)



Pros	Cons
Low-cost carrier PCB	More chip-level design effort
Only IF and LO distribution, SPI, VDD on PCB	Antennas may not be wideband
Can be used at high frequency	Possible air gap between Quartz and silicon

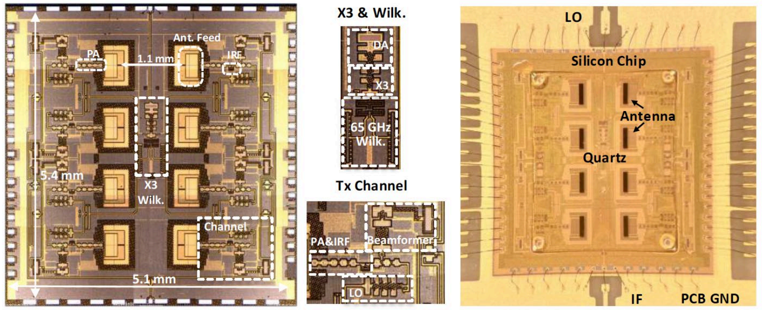


Die Photo

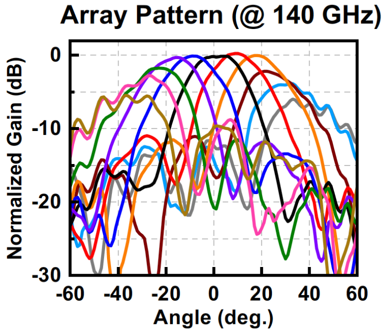


Receiver chip with antenna and quartz

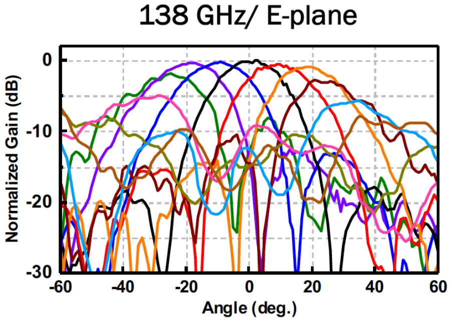
RX Chip

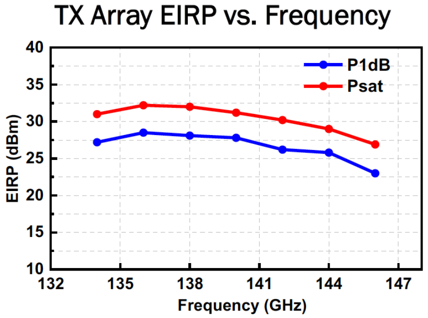


TX Chip



RX Meas



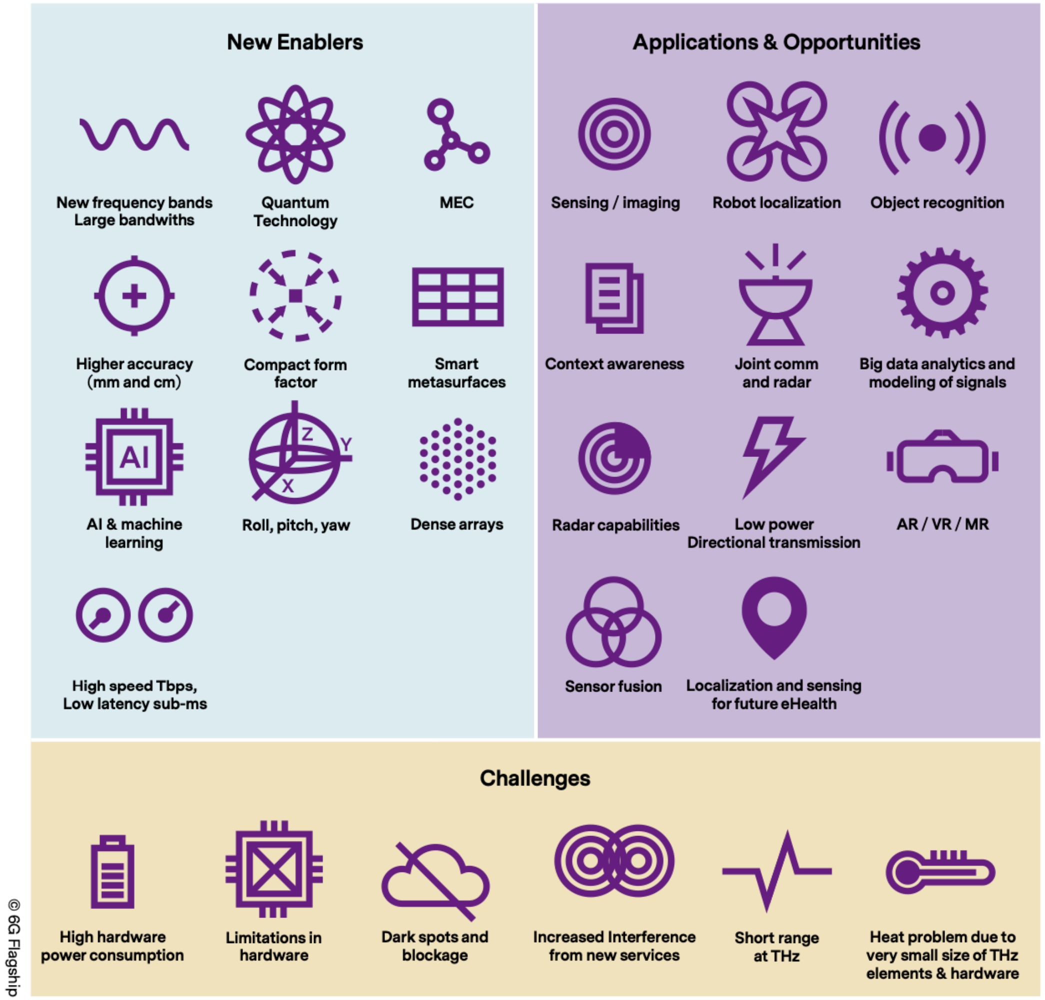


TX Meas

Li & Rebiez, ”A 140GHz CMOS RFSOI Transmit-Receive Phased-Array Wireless Link with 11–12Gbps and 16 and 64-QAM Operation,” IMS2022

Enabling technologies, 6G new application opportunities and technological challenges

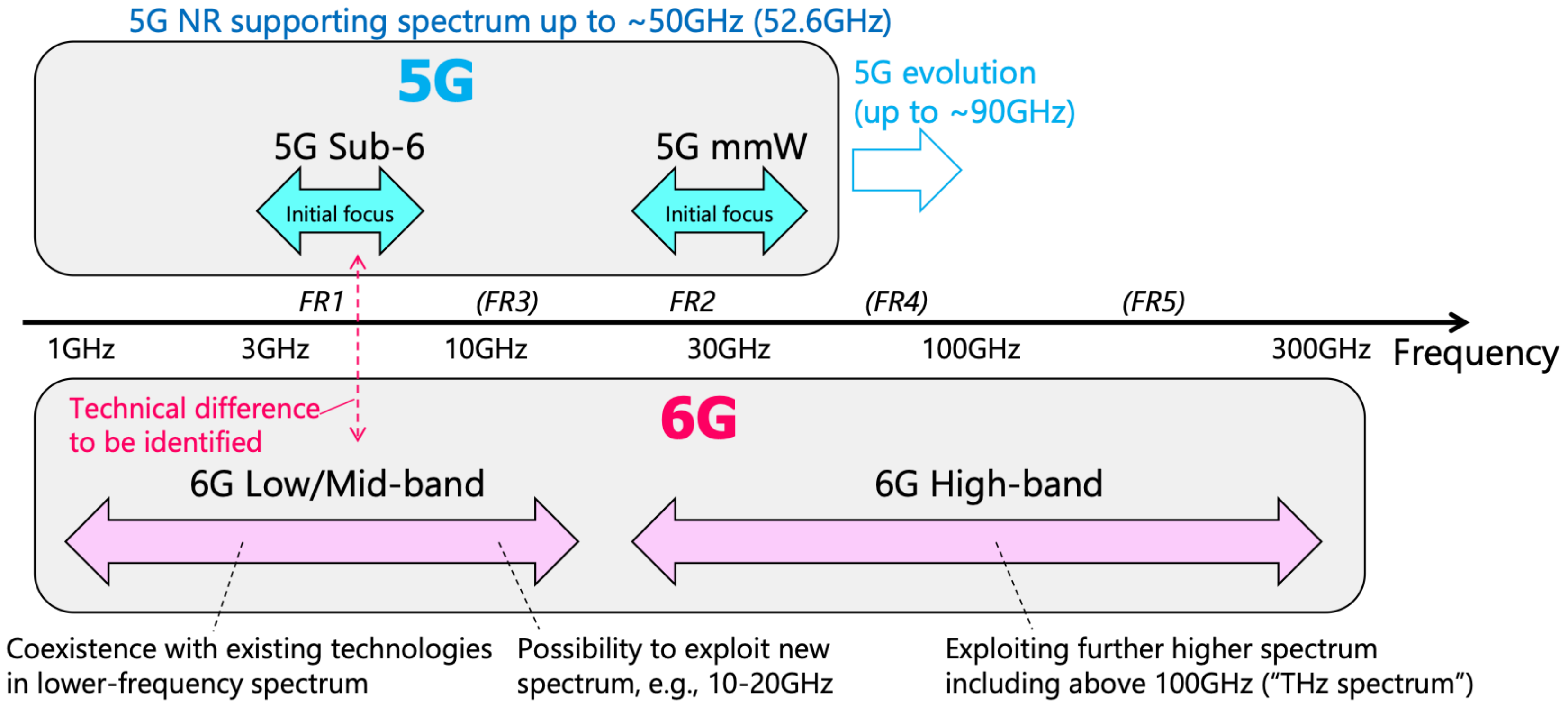
- RF spectrum for future localization and sensing systems
  - Leap in available bandwidths and carrier frequencies
- The transition to THz frequencies has several important benefits.
  - Signals at these frequencies are unable to penetrate objects, leading to a more direct relation between the propagation paths and the propagation environment.
  - At higher frequencies, larger absolute bandwidths are available, leading to more resolvable multi-path in the delay domain with more specular components.
  - Shorter wavelengths imply smaller antennas, so that small devices can be packed with tens or hundreds of antennas, which will be beneficial for angle estimation.
  - The high-rate communication links offered by 6G will be able to be leveraged to quickly and reliably share map and location information between different sensing devices.
- **6G is not not just new frequency bands – it will be AI-enabled for sensing, communications and imaging**



http://jultika.oulu.fi/files/isbn9789526226743.pdf

6G Spectrum Extension

- 5G NR supports frequency bands up to 52.6 GHz, and extension to approximately 90 GHz for future release
- 6G exploits higher frequency bands than 5G such as “millimeter wave” and “terahertz wave” (~300 GHz), and remarkably wider bandwidth can achieve extreme high data rates exceeding 100 Gbps



http://6gglobal.org/download/2-1.%20NAKAMURA,%20Takehiro.pdf

Summary

HETEROGENEOUS
INTEGRATION ROADMAP

- We are at a unique point in time when there is a global recognition on the critical roles of semiconductor and microelectronics as foundational pillars to nations economies.
- There is immense need for a Heterogeneous Integration technology roadmap addressing future vision, difficult challenges, and potential solutions to pave the way for Microelectronics Resurgence
- Our Greatest Challenge are ourselves : will we take full advantage of unique opportunities today collaboratively advancing the the science & technology for the benefit of humankind.
- Heterogeneous integration (e.g SiP & Chiplets & more) is a broad & deep base for Science & Technology Renaissance & Microelectronics Resurgence

Thank You!

https://eps.ieee.org/technology/heterogeneous-integration-roadmap.html

IEEE

IEEE photonics Society

semi

IEEE ELECTRONICS PACKAGING SOCIETY

ASME SETTING THE STANDARD

ELECTRON DEVICES SOCIETY®

Backups